New type of stable Q balls in the gauge-mediated supersymmetry breaking

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(June 13, 2000)

We obtain a new type of a stable Q ball in the context of gauge-mediated supersymmetry breaking in minimal supersymmetric standard model. It is so-called gravity-mediation type of Q ball, but stable against the decay into nucleons, since the energy per unit charge is equal to gravitino mass $m_{3/2}$, which can be smaller than nucleon mass in the gauge-mediation mechanism. We consider the cosmological consequences in this new Q-ball scenario, and find that this new type of the Q ball can be considered as the dark matter and the source for the baryon number of the universe simultaneously.

hep-ph/0006128

The standard cosmology provides a whole description from a few minutes after "big bang" to now [1]. One of the evidence which supports it is the nucleosynthesis, which successfully predicts cosmological abundances of all light elements. It requires that there is a small asymmetry of the baryons in the universe: $\eta_B = n_B/n_\gamma \sim 10^{-10}$, where n_B and n_γ denote the number density of the baryon and photon, respectively. This and other observations show that our universe is made almost entirely of matters and devoid of antimatters. Such matter-antimatter asymmetry is produced by baryogenesis, which takes place nonthermally through baryon and CP violating interactions in the very early universe.

On the other hand, inflation solves many problems which cannot be explained in the standard cosmology, such as the homogeneity, flatness, and monopole problems. Inflation thus predicts that $\Omega_{\rm tot} = 1$, where Ω is the density parameter, the ratio of the density to the critical density $\rho_c \simeq 1.9 \times 10^{-29} h^2$ g/cm^3, and h is the Hubble parameter normalized by 100 km/sec/Mpc. However, $\eta_B \sim 10^{-10}$ corresponds to $\Omega_B h^2 \simeq 0.02$, far less than the prediction from the inflation. Even if one does not consider the inflation, $\Omega_{\rm matter} \gtrsim 0.2$ is expected from observations for dynamical properties of galaxies and clusters of galaxies. Therefore, most of the density of the universe has to be in the form of dark matter.

Several mechanisms for creating baryons have been proposed, but none of them explain directly why the universe has almost the same amount of baryons and the dark matter. Their answer is that it is a numerical coincidence. However, the Q ball provides a natural scenario for explaining both of them simultaneously [2,3].

In the supersymmetric standard models, Affleck-Dine (AD) mechanism [4] is the most promising procedure for the baryogenesis. In the minimal supersymmetric standard model (MSSM), there are many flat directions consist of squarks and sleptons [5], which can be identified as the AD field. Its potential is almost flat but slightly lifted up by effects of supersymmetry (SUSY) breaking. For the mechanism of SUSY breaking, there are two famous scenarios: the gravity- and gauge-mediated SUSY breakings. It was believed that the AD field stays at large field value at the inflationary stage, and, when the Hubble parameter becomes as small as the AD scalar mass after inflation, rolls down homogeneously its potential with rotation, making the baryon number of the universe.

Recently, however, it was revealed that the AD field does not evolve homogeneously, but feels spatial instabilities, which grow nonlinear and form into Q balls [2]. A Q ball is a kind of the nontopological soliton, whose stability is guaranteed by the nonzero charge Q [6,7]. In the context of the AD baryogenesis, the charge Q is the baryon number B. In the gauge-mediated SUSY breaking, a Q ball is stable against the decay into nucleons, provided that its charge is large enough so that its energy per unit charge is less than nucleon mass: $E_Q/Q \simeq m_\phi Q^{-1/4} < 1$ GeV [8,2], where $m_\phi \sim 1$ TeV, is the mass of AD field. Therefore, the Q ball itself can be a candidate for the dark matter. On the other hand, in the gravity-mediated SUSY breaking, the energy of a Q ball per unit charge is essentially constant: $E_Q/Q \simeq m_\phi > 1$ GeV [3]. Thus, it should decay into nucleons, and the dark matter will be lightest supersymmetric particles (neutralinos) produced in Q-ball decays. In either case, the dark matter and the baryon number of the universe can be explained simultaneously by the Q-ball formation through the AD mechanism.

In all the previous studies of Q balls in the context of SUSY breaking, the effects of gauge- and gravity-mediations are considered separately. However, it is natural to have both effects in the gauge-mediated SUSY breaking scenario, since the gravity-mediation effects will dominate over the gauge ones at the large field value. Cosmology including AD baryogenesis in such more realistic SUSY breaking scenario was considered in Ref. [9]. There, AD field is regarded as a homogeneously rotating condensate, but we notice that it will form Q balls due to the instabilities of the field. Particular interest is the smallness of the gravitino mass comparing with that in the gravity-mediation scenario. It usually ranges between 100 keV and 1 GeV. Therefore, we can imagine

a new type of a stable Q ball: the profile is the same as that in the gravity-mediation, but its energy per unit charge is less that 1 GeV because of the small gravitino mass. In this Letter, we study the cosmological consequences of Q balls (baryogenesis and the dark matter) in the gauge-mediated SUSY breaking, taking into account the gravity-mediation effects at large field value.

To be concrete, let us assume the following potential for the AD field,

$$V(\Phi) = m_\phi^4 \log\left(1 + \frac{|\Phi|^2}{m_\phi^2}\right)$$
$$+ m_{3/2}^2 |\Phi|^2 \left[1 + K \log\left(\frac{|\Phi|^2}{M_*^2}\right)\right], \quad (1)$$

where $m_{3/2}$ is the gravitino mass, $K(<0)$ term a one-loop correction, [†] M_* the renormalization scale, and we assume that the second term should be neglected for small field value. This is nothing but the sum of the potentials for the gauge- and gravity-mediation mechanisms studied previously [2,3,10,11]. However, as we mentioned earlier, the gravitino mass is considerably smaller. The second term will dominate the potential when

$$\phi \gtrsim \phi_{eq} \equiv \sqrt{2}\frac{m_\phi^2}{m_{3/2}}, \quad (2)$$

where $\Phi = \phi \exp(i\omega t)/\sqrt{2}$. In this case, a new type of a stable Q ball is produced. Its property is very similar to that in the gravity-mediation, such as [3,12]

$$R_Q \simeq |K|^{-1/2} m_{3/2}^{-1}, \qquad \omega \simeq m_{3/2},$$
$$\phi \simeq |K|^{3/4} m_{3/2} Q^{1/2}, \qquad E_Q \simeq m_{3/2} Q, \quad (3)$$

but, as can be seen from the last equation, it is stable against the decay into nucleons. In the opposite case, the Q-ball properties are the same as in the gauge-mediation only [2]:

$$R_Q \simeq m_\phi^{-1} Q^{1/4}, \qquad \omega \simeq m_\phi Q^{-1/4},$$
$$\phi \simeq m_\phi Q^{1/4}, \qquad E_Q \simeq m_\phi Q^{3/4}. \quad (4)$$

The energy per unit charge can be treated from unified viewpoint. The largest charge of the Q ball formed depends linearly on the initial charge density of the AD field as [10,11]

$$Q \simeq \beta \frac{q(0)}{m_{3/2}^3} \simeq \beta \left(\frac{\phi(0)}{m_{3/2}}\right)^2, \quad (5)$$

[†]Usually, gaugino contributions to K is dominated and K becomes negative. However, if $K > 0$ by some large Yukawa couplings, the AD field can be stabilized and Q balls can be created only for $\phi \lesssim \phi_{eq}$, where ϕ_{eq} is defined in Eq.(2).
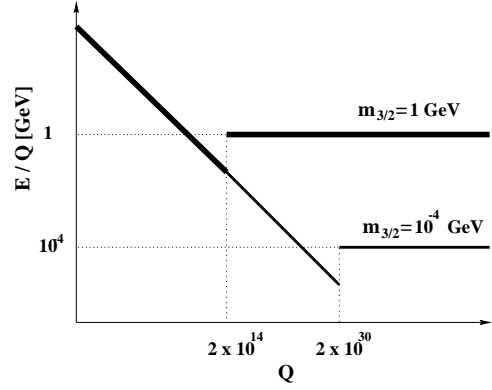

FIG. 1. Dependence of the energy per unit charge on the charge of the Q ball. Gauge-mediation type of Q ball are formed with less charge, while gravity-mediation type has larger with E/Q fixed.

where $\beta \lesssim 1$ [12], and we use $q = \omega\phi^2 \simeq m_{3/2}\phi^2$. It can be understood by estimating Q-ball charge in the standard way. The charge is given by

$$Q = \int d^3x\, \omega\phi^2 = \left(\frac{\pi}{2}\right)^{3/2} \omega\phi_0^2 R^3 = \beta'\left(\frac{\phi_0}{m_{3/2}}\right)^2, \quad (6)$$

where we assume the Gaussian profile ansatz [3], $\phi = \phi_0 \exp(-r^2/R^2)$, which is a very good approximation, and use relations (3), and $\beta' \simeq 2 \times 10^3 (|K|/0.01)^{-3/2}$. The discrepancy of coefficients β and β' comes from the fact that $\phi(0) \neq \phi_0$ and there are more than one Q balls with charges of the same order of magnitude as the largest.

Inserting it into Eq.(2), we obtain

$$m_{3/2} \gtrsim (2\beta)^{1/4} m_\phi Q^{-1/4}. \quad (7)$$

The right hand side of this equation is identical to the expression for the energy per unit charge of the gauge-mediation besides the factor of order unity. The energy per unit charge of the Q ball is written as

$$\frac{E_Q}{Q} = \begin{cases} m_\phi Q^{-1/4} & \phi \lesssim \phi_{eq} \\ m_{3/2} & \phi \gtrsim \phi_{eq} \end{cases}, \quad (8)$$

which is shown in Fig. 1. The gap on the boundary should disappear and both sides of the curves will be smoothly connected because Q balls formed in this region are not the exact type of either (3) or (4), but will show properties between them.

Since Q balls are stable even for $\phi \gtrsim \phi_{eq}$, where the gravity-mediation effect is crucial, the baryon number in the universe should be explained by the baryons evaporated from Q balls, as is the same as for the gauge-mediation type [13]. The evaporation rate of the Q ball is [13]

$$\Gamma_{evap} \equiv \frac{dQ}{dt} = -\alpha\mu T^2 4\pi R_Q^2, \quad (9)$$

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where μ is a chemical potential of the Q ball, which is estimated as $\mu \simeq \omega$ because ω is energy of ϕ-field inside the Q ball. Although the mass of the (free) AD particle m_ϕ is affected by thermal corrections, which should be changed as $m_\phi \to m_\phi(T) \sim T$, at $T \gg m_\phi$, the gravitino mass is not affected, since particles coupled to the AD field are decoupled from thermal bath when the AD field has a large vacuum expectation value. At $T \gtrsim m_\phi$, large numbers of ϕ-particles are in thermal bath outside Q balls, so $\alpha \sim 1$. On the other hand, since only light quarks are in thermal bath at $T \lesssim m_\phi$, the corresponding cross section is highly suppressed by the heavy gluino exchanges, and $\alpha \simeq (T/m_\phi)^2$.

However, if the rate of the charge diffusion from the "atmosphere" of the Q ball is smaller than the evaporation rate, chemical equilibrium will established there, which results in the suppression of the evaporation [14]. The diffusion rate is [14]

$$\Gamma_{\text{diff}} \equiv \frac{dQ}{dt} = -4\pi\zeta R_Q D\mu_Q T^2, \tag{10}$$

where $D = a/T$ with $a \simeq 4-6$, and $\zeta \sim 1$.

The time scale of charge transportation is determined by the diffusion when $\Gamma_{\text{diff}} \lesssim \Gamma_{\text{evap}}$. It holds for $T \gtrsim T_* \equiv a^{1/3}|K|^{1/6}(m_{3/2}m_\phi^2)^{1/3}$. In this case, using Eqs.(3) and (10), and assuming the radiation-dominated universe, $t = AM/T^2$, where $A \approx 0.2$ and $M \simeq 2.4 \times 10^{18}$ GeV, we obtain

$$\frac{dQ}{dT} = \frac{8\pi aAM}{|K|^{1/2}T^2}. \tag{11}$$

On the other hand, when $T \lesssim T_*$, the diffusion effect is negligible, and Eq.(11) should be replaced by

$$\frac{dQ}{dT} = \frac{8\pi AMT}{|K|m_{3/2}m_\phi^2}. \tag{12}$$

Therefore, total amount of the charge evaporated from the Q ball is

$$\Delta Q \simeq 12\pi AM \left(\frac{a}{|K|}\right)^{2/3} (m_{3/2}m_\phi^2)^{-1/3}. \tag{13}$$

Provided that the initial charge of the Q ball is larger than the evaporated charge, we regard that the Q ball survives from evaporation, and contributes to the dark matter of the universe:

$$Q_{\text{init}} \gtrsim \Delta Q \simeq 9.8 \times 10^{18} \left(\frac{m_{3/2}}{\text{GeV}}\right)^{-1/3} \left(\frac{m_\phi}{\text{TeV}}\right)^{-2/3}, \tag{14}$$

where we set $a = 4$ and $|K| = 0.01$.

Now we can relate the baryon number and the amount of the dark matter in the universe. As mentioned above, the baryon number of the universe should be explained by the amount of the charge evaporated from Q balls, ΔQ, and the survived Q balls become the dark matter. If we
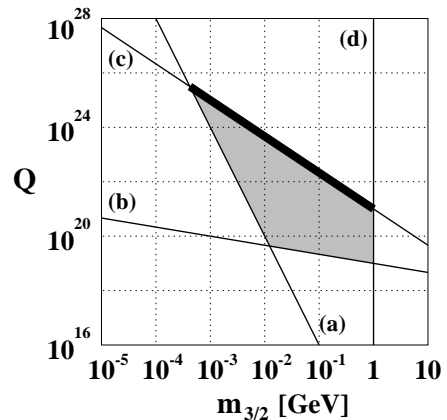

FIG. 2. Summary of constraints on $(Q, m_{3/2})$ plain for $|K| = 0.01$. (a), (b), and (c) represent for the constraints (16), (14) and (15) with $m_\phi = 1$ TeV, respectively. (d) shows the condition for the gravity-mediation type of the Q ball to be stable.

assume that Q balls do not exceed the critical density of the universe, i.e., $\Omega_Q \lesssim 1$, and the baryon-to-photon ratio as $\eta_B \sim 10^{-10}$,

$$Q \lesssim 3.2h^2 \times 10^{21} \left(\frac{m_{3/2}}{\text{GeV}}\right)^{-4/3} \left(\frac{m_\phi}{\text{TeV}}\right)^{-2/3}. \tag{15}$$

Rewriting Eq.(7), we have

$$Q \gtrsim 2\beta \times 10^{12} \left(\frac{m_\phi}{\text{TeV}}\right)^4 \left(\frac{m_{3/2}}{\text{GeV}}\right)^{-4}. \tag{16}$$

Combining this constraint with Eqs.(14) and (15), together with $m_{3/2} \lesssim 1$ GeV, which implies that the gravity-mediation type of the Q ball is stable against the decay into nucleons, we obtain the allowed region for the new type of the stable Q ball explaining the baryon number of the universe. Figure 2 shows the allowed region on $(Q, m_{3/2})$ plane for $m_\phi = 1$ TeV. The shaded regions represent that the new type of stable Q balls are created, and the baryon number of the universe can be explained by the mechanism mentioned above. Furthermore, the new type of stable Q balls contribute crucially to the dark matter of the universe at present, if the Q balls have the charge given by the thick line in the figure. Notice that Q balls with very large charge are not allowed because they will overclose the density of the universe. [‡] Therefore, the initial conditions for the AD field is restricted severely [12].

One may wonder if these new type of stable Q balls can be detected. When a Q ball collides with nucleons,

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[‡] If the baryons are produced by other mechanism, larger Q balls can be allowed. In this case, however, a nice relation between the densities of the baryon and the dark matter does not hold.
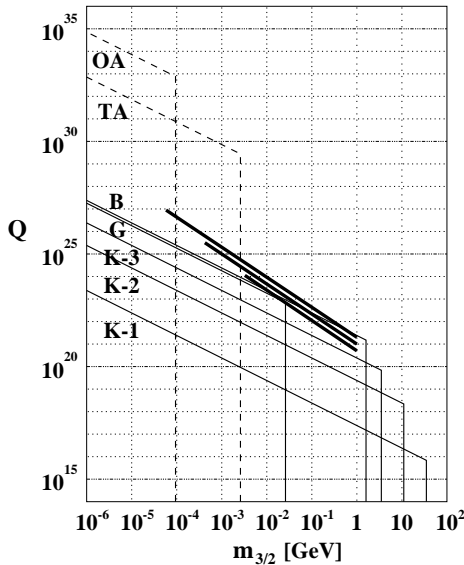
FIG. 3. Restrictions of ENQBs by several experiments on $(Q, m_{3/2})$ plain for $|K| = 0.01$. We show the regions currently excluded by BAKSAN (B), Gyrlyand (G), and Kamiokande (K-1, K-2, K-3), and to be searched by the Telescope Array Project (TA) and OWL-AIRWATCH (OA) in the future. The thick lines represent for the gravity-mediation type of the Q ball to be both the dark matter and the source for the baryons of the universe for $m_\phi = 300$ GeV, 1 TeV, and 3 TeV from the top to the bottom.

they enter the surface layer of the Q ball, and dissociate into quarks, which are converted into squarks. In this process, Q balls release ~ 1 GeV energy per collision by emitting soft pions. This process is the basis for the Q-ball detections [15,16], which is called (Kusenko-Kuzmin-Shaposhnikov-Tinyakov) KKST process in the literature. It occurs for electrically neutral Q balls (ENQB). For electrically positively charged Q balls (EPCQB), the KKST process is strongly suppressed by Coulomb repulsion, and only electromagnetic processes will take place. For electrically negatively charged Q balls (ENCQB), the both KKST and electromagnetic processes occur, but the former is dominant, which is essentially the same as for ENQBs.

In either case, the detection is more difficult than for the gauge-mediation type of Q balls, since the geometrical cross section is smaller for large Q, and the Q-ball mass is larger for the same Q, which results in small flux. With the discussions similar to Ref. [16], we can restrict the parameter space $(Q, m_{3/2})$ by the several experiments. Fig. 3 shows the results for ENQBs. Lower left regions are excluded by the various experiments. The present available data prohibit the stable gravity-mediation type Q balls with large gravitino mass to be both the dark matter and the source of the baryons, and future experiments such as the Telescope Array Project or the OWL-AIRWATCH detector may detect this type of Q balls with an interesting gravitino mass ~ 100 keV.

For EPCQBs with $Z = 1$, similar constraints as for ENQBs are put by the MACRO experiment [12].

In summary, we have obtained a new type of a stable Q ball in the context of gauge-mediated SUSY breaking in MSSM. Many properties are the same as the gravity-mediation type of Q ball, but it is stable against the decay into nucleons, since the energy per unit charge is equal to the gravitino mass $m_{3/2}$, which can be smaller than nucleon mass of 1 GeV in the gauge-mediation mechanism. We have considered the cosmological consequences in this new Q-ball scenario. Because of its stability, it can be a nice candidate for the dark matter of the universe. In the present case, the baryons are produced only by evaporation from Q balls, since (almost) all the baryons are trapped in Q balls during their formation. We have found that the Q ball with $Q \sim 10^{25} - 10^{22}$ can account for both the dark matter and the baryon number of the present universe for $m_{3/2} \simeq 10^{-4} - 10^{-1}$ GeV and $m_\phi = 1$ TeV, and such Q balls may be detected by the future experiments.

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